Active Metal Brazing and Adhesive Bonding of Titanium to C/C Composites for Heat Rejection System

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Robust assembly and integration technologies are critically needed for the manufacturing of heat rejection system (HRS) components for current and future space exploration missions. Active metal brazing and adhesive bonding technologies are being assessed for the bonding of titanium to high conductivity Carbon-Carbon composite sub components in various shapes and sizes. Currently a number of different silver and copper based active metal brazes and adhesive compositions are being evaluated. The joint microstructures were examined using optical microscopy, and scanning electron microscopy (SEM) coupled with energy dispersive spectrometry (EDS). Several mechanical tests have been employed to ascertain the effectiveness of different brazing and adhesive approaches in tension and in shear that are both simple and representative of the actual system and relatively straightforward in analysis. The results of these mechanical tests along with the fractographic analysis will be discussed. In addition, advantages, technical issues and concerns in using different bonding approaches will also be presented.

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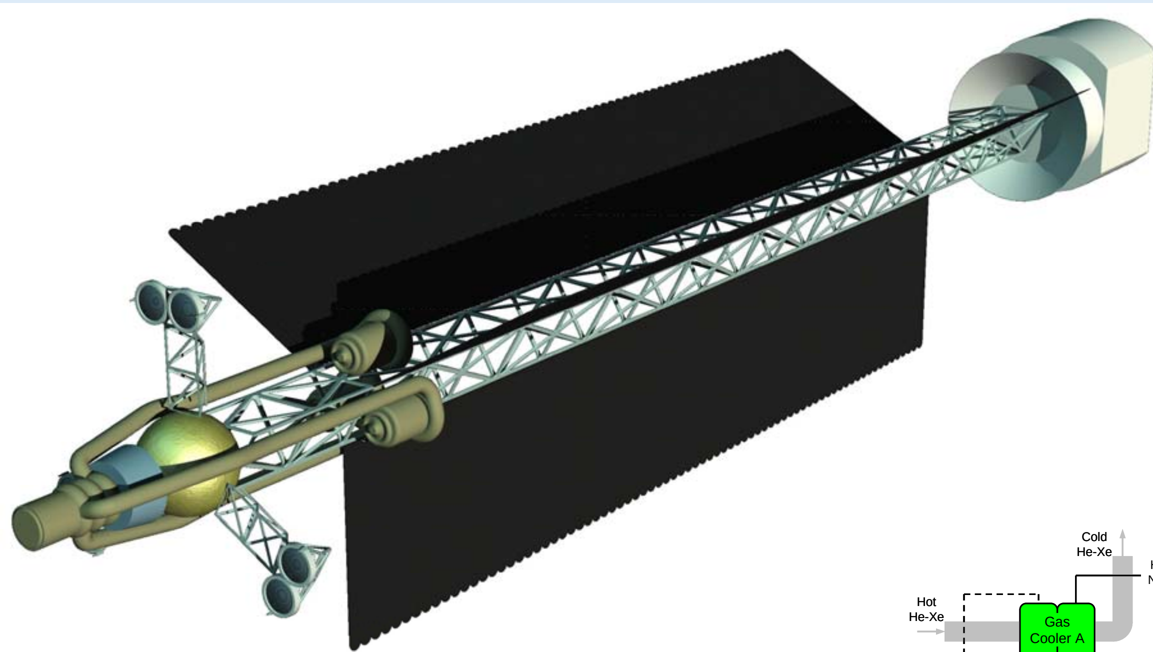
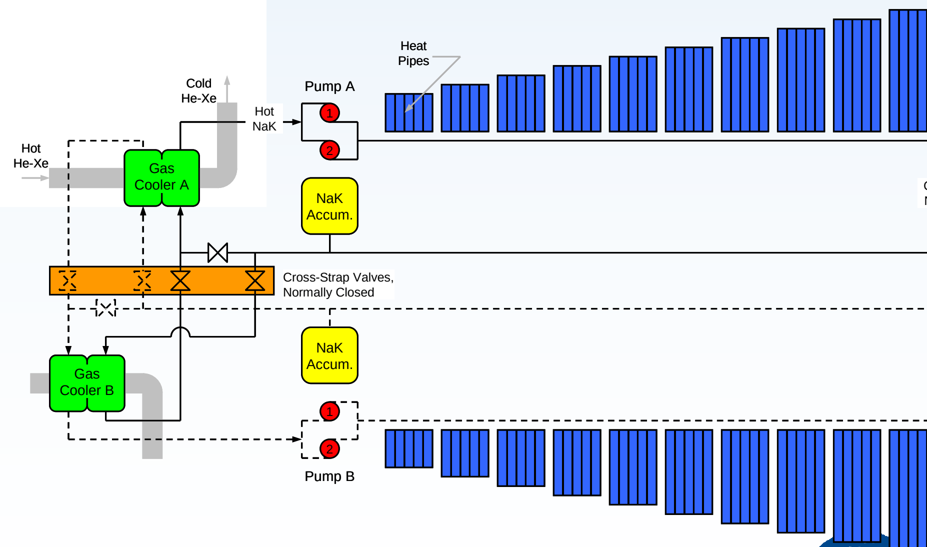
Outline

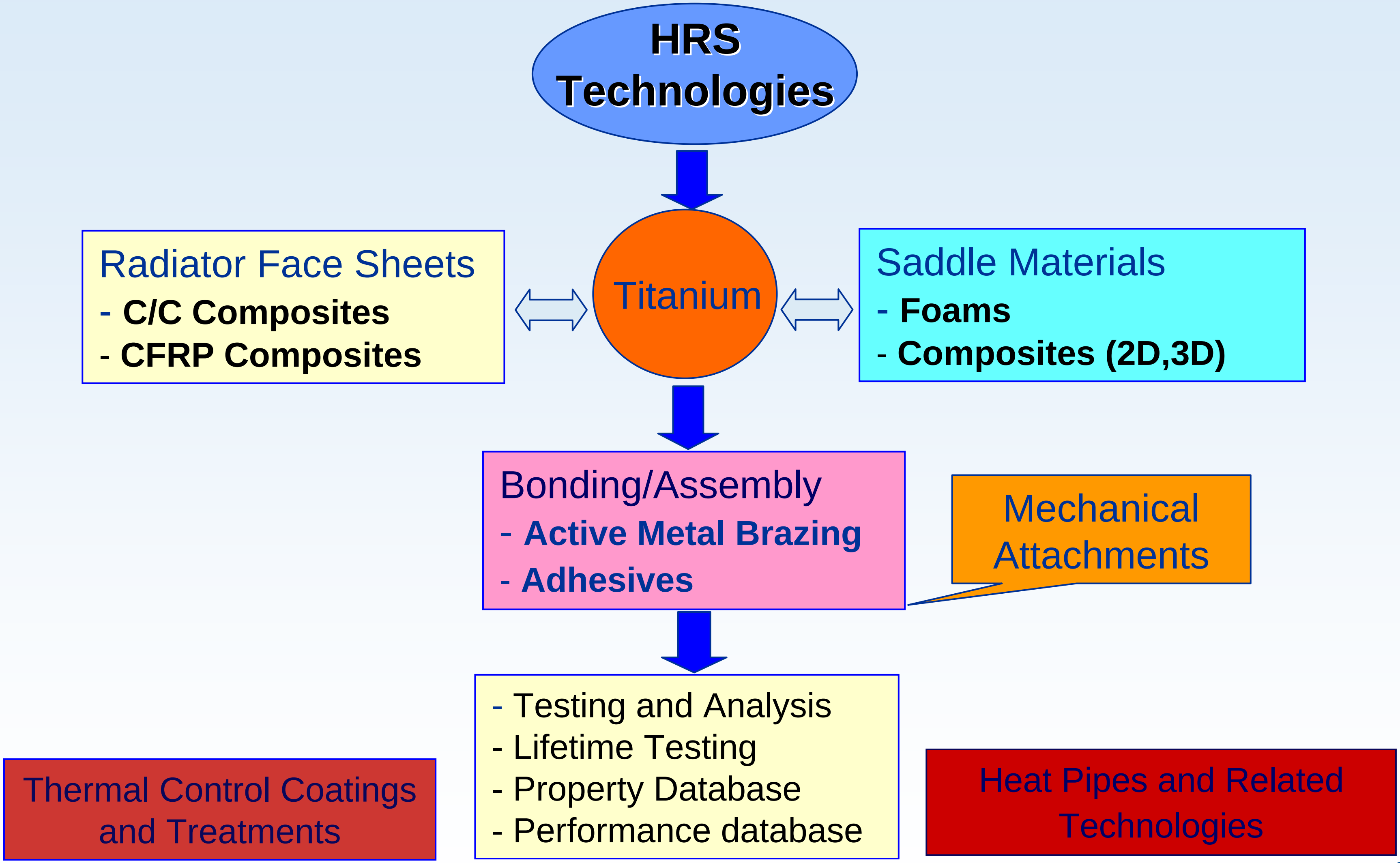
- **Need for Joining and Integration Technologies**
- **Challenges in Bonding of Metal-Composite System**
    - ***Thermal Expansion***
    - ***Joint Design and Testing***
- **Active Metal Brazing of Titanium to C/C Composites**
    - ***Microstructural Analysis of Brazed Joints***
    - ***Mechanical Behavior***
- **Adhesive Bonding of Titanium to C/C Composites**
    - ***Adhesive Selection and Joint Microstructure***
    - ***Mechanical Behavior***
- **Summary and Conclusions**

Thermal Management Technologies are Critical for Space Exploration Systems

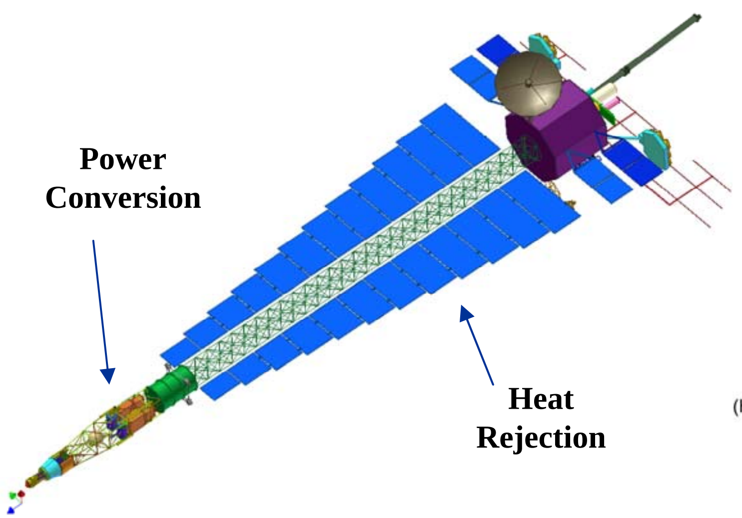


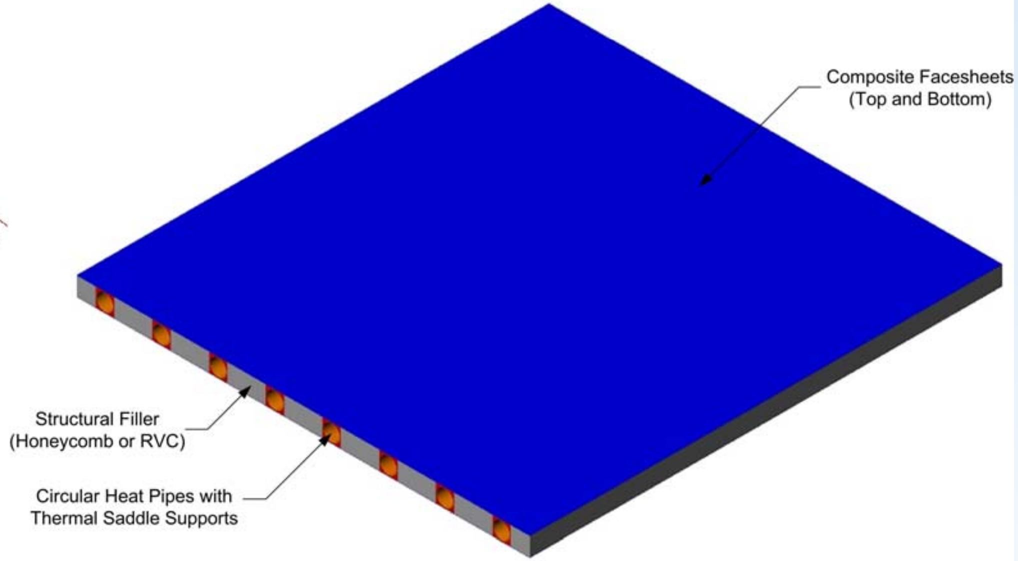


Heat Rejection System: Materials and Technologies

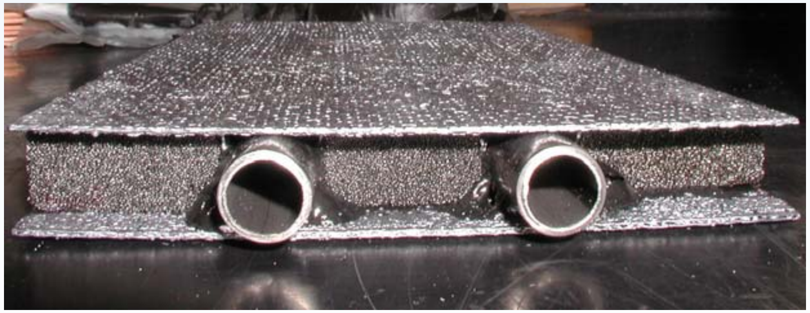


Assembly and Integration Technologies are Key to Manufacturing of Heat Rejection System



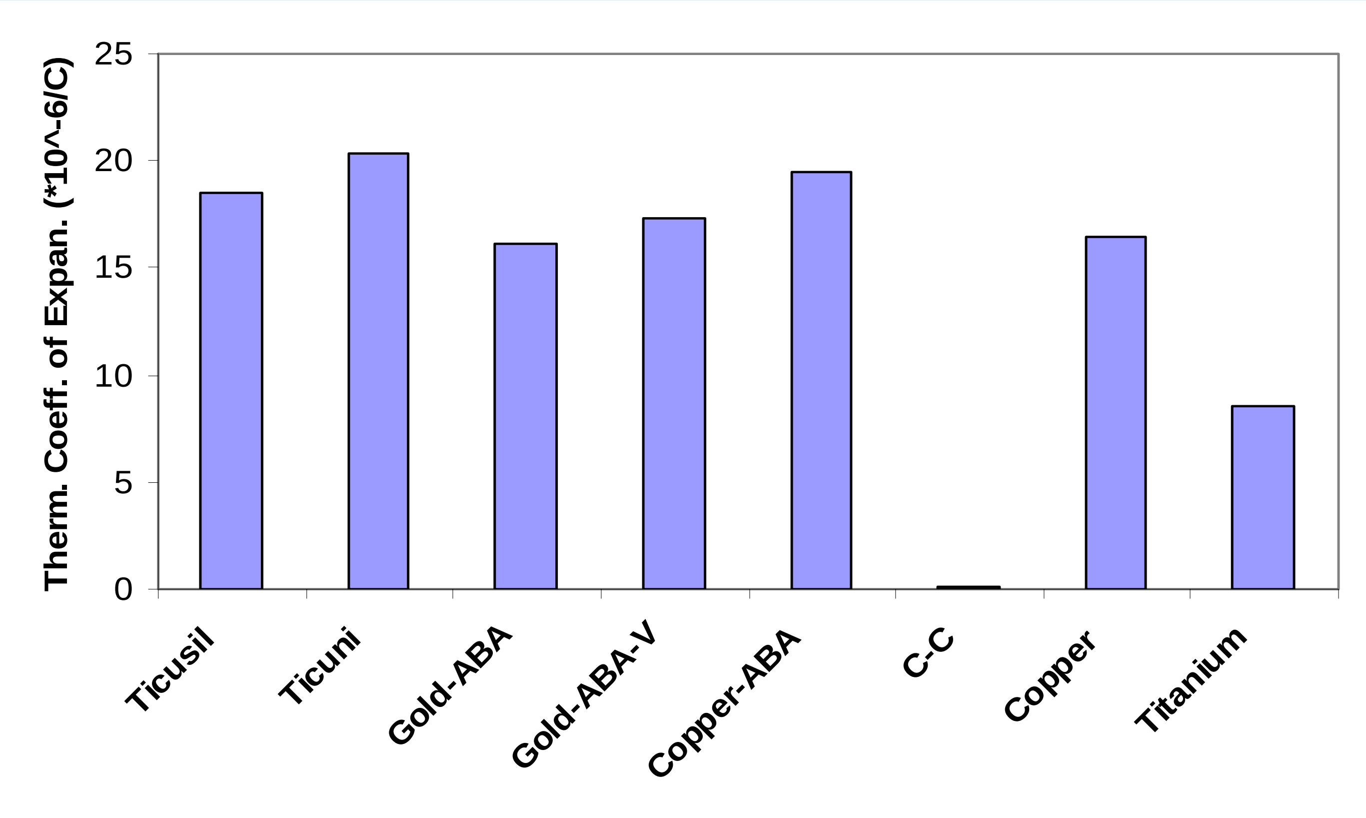


Advanced C/C Composite Radiators



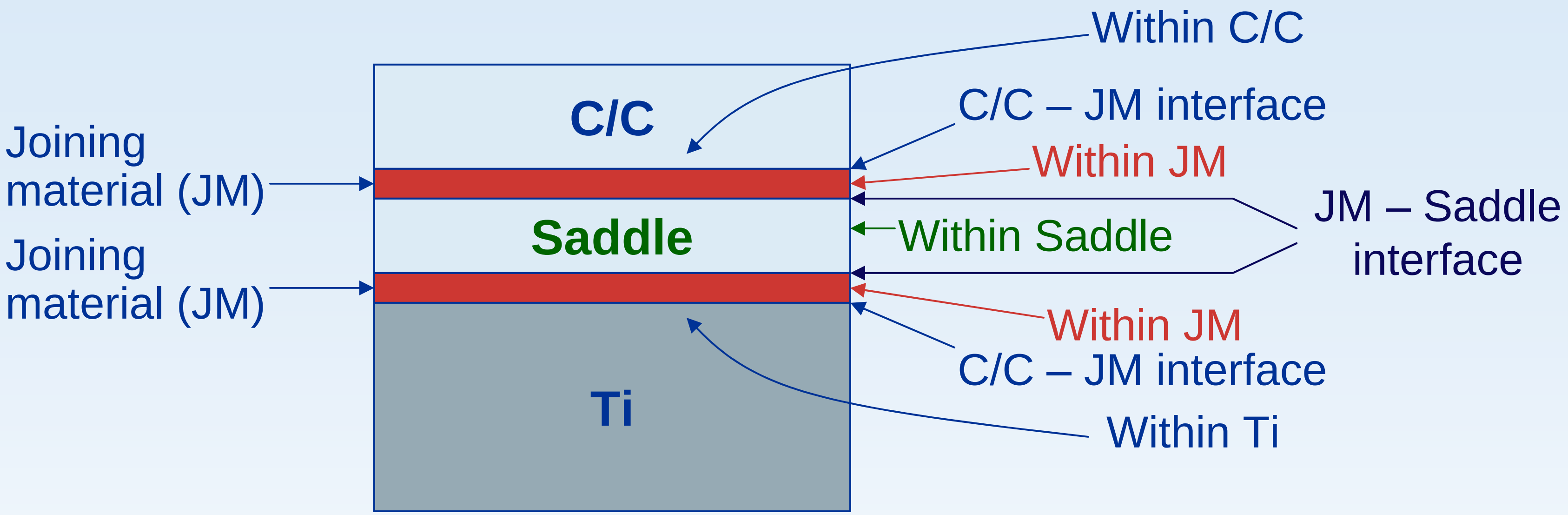
Assembly of Composites with Titanium Tubes

Thermal Expansion Mismatch Issues are Critical in Brazing of Metal-Composite System



Innovative joint design concepts, new braze materials, and robust brazing technology development are needed to avoid deleterious effects of thermal expansion mismatch.

Locations of Potential Joint Failure



In addition the geometry of joining surfaces will affect strength of joint and influence spreading of joint material: flat to flat, flat to tube, curved surfaces…

Therefore, knowing the location of joint failure is critical

- **Weakest link requiring further improvement**
- **Affects interpretation of results (material or test-dependent property)**

Key factor: Bonded area dictated by braze composition and applied pressure, C/C constituent composition, fiber orientation, geometry of joined surface

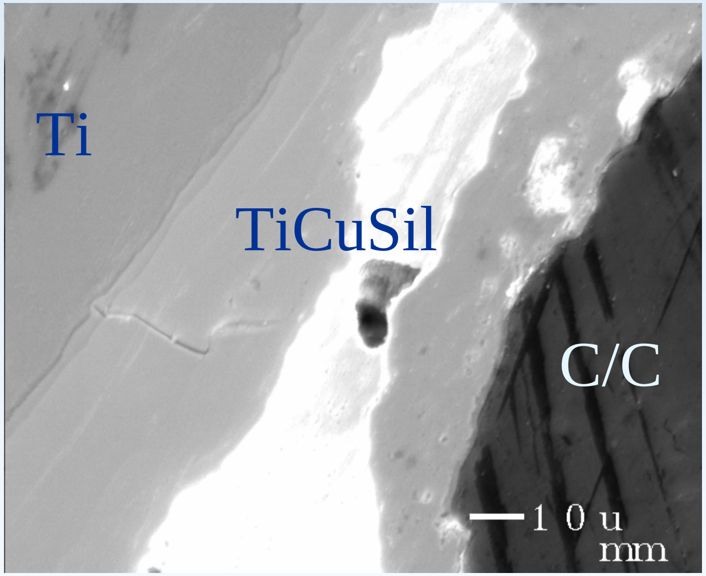
Active Metal Brazing of Titanium Tubes and Plates to C/C Composites

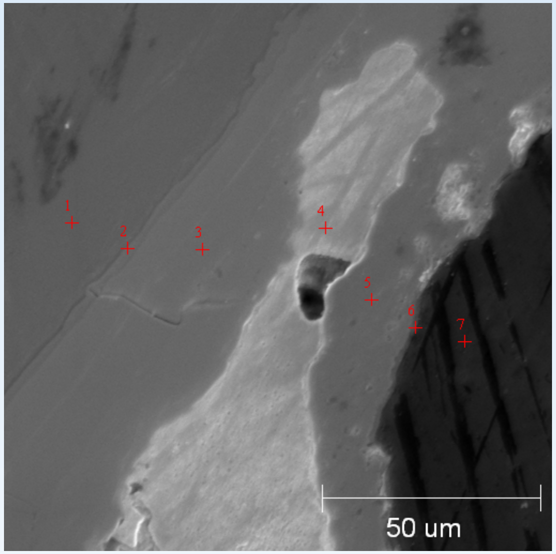
Active Metal Brazing

- **Ti tubes and plates brazed to P120 CVI C/C composite (Goodrich)**
- **Several braze/solder compositions compared (processing Temp):**
  - TiCuSil (910 C) foil and paste
  - CuSil-ABA (820 C) foil and paste
  - CuSin-1ABA foil (810 C)
  - Incusil foil (725 C)
  - S-Bond solder (~ 300 C)
- **Two tests have proved successful:**
  - Butt Strap Tension (BST)
  - Tube-Plate Tensile Test

- ***<u>Require</u> good wetting, bonding and spreading properties***
- ***<u>Desire</u> minimal residual stress induced cracking in C/C***

Microstructure of Brazed Ti Tubes and C-C Composites using TiCuSil Paste

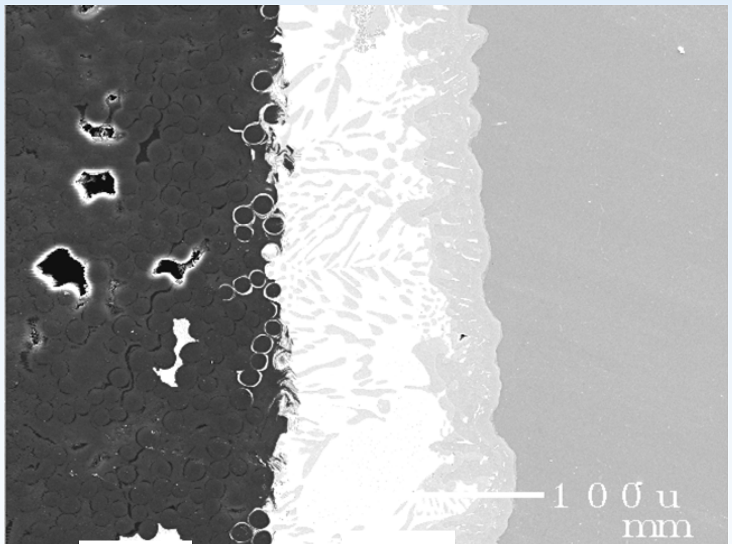




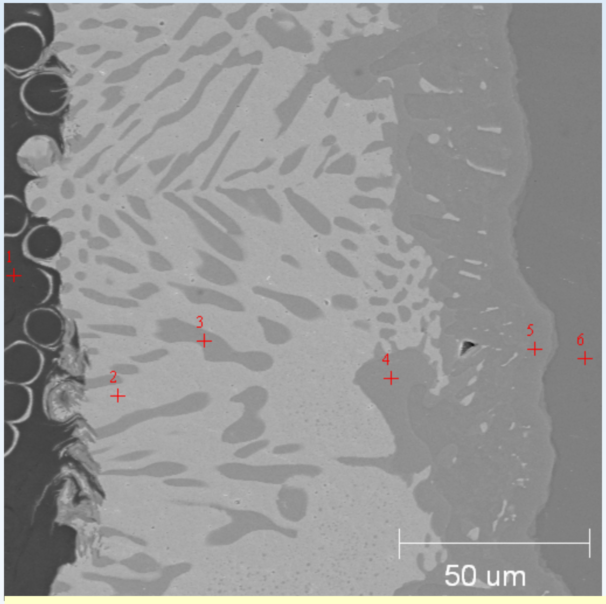
Compositions (atm%):

1) 92%Ti, 7%Cu, 1%Ag
2) 70%Ti, 30%Cu
3) 42%Ti, 54%cu, 4%Ag
4) 4%Cu, 96%Ag
5) 33%Ti, 63%Cu, 4%Ag
6) 84%Ti, 13%Cu, 3%Ag
7) 100%C

Microstructure of Brazed Ti and C-C Composites using CuSil ABA Paste



P120 CuSil ABA Ti



Composition:

1) 100%C

2) 1%Ti, 3%Cu, 96%Ag

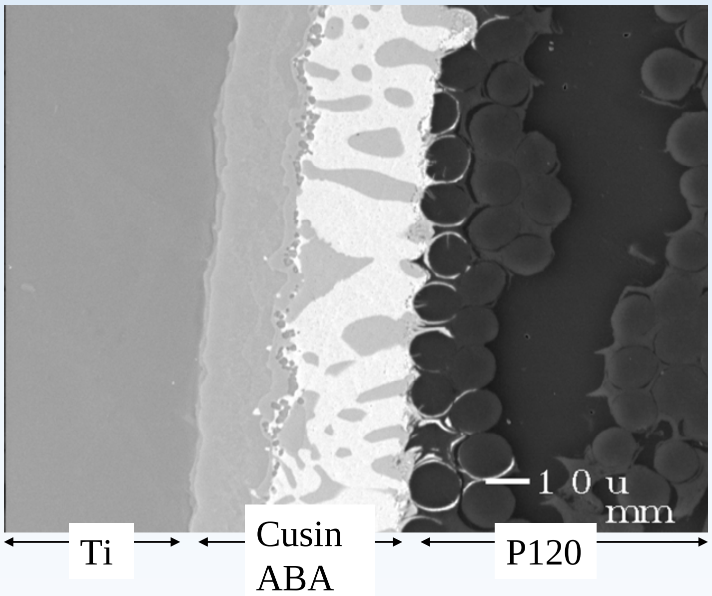
3) 1%Ti, 95%Cu, 4%Ag

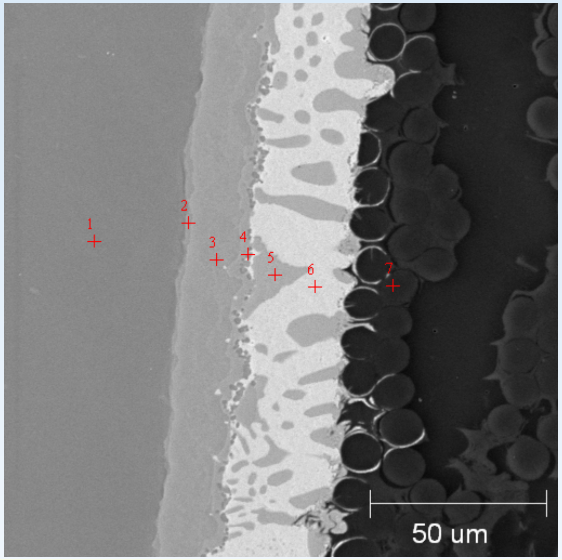
4) 15%Ti, 80%Cu, 4%Ag

5) 43%Ti, 54%Cu, 3%Ag

6) 99%Ti, 1%Ag

Microstructure of Joint Interface in Ti and C-C Composites Brazed using CuSin ABA Foil



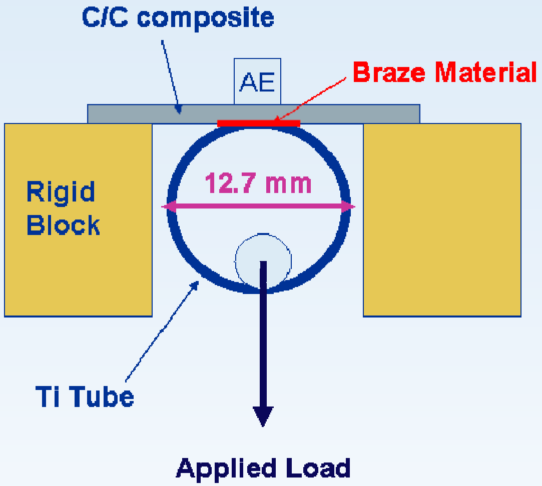


Composition:

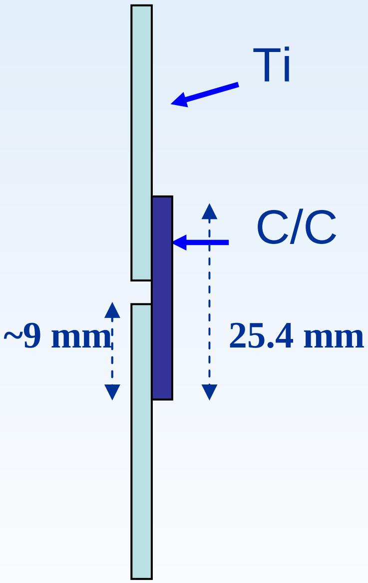
1) 98% Ti, 1%Cu, 0.5% Ag, 0.5% Sn
2) 61%Ti, 36%Cu, 2%Ag, 2%Sn
3) 37% Ti, 59%Cu, 2%Ag, 2%Sn
4) 28% Ti, 47%Cu, 25% Ag
5) 3%Ti, 84%Cu, 13%Ag,
6) 1%Ti, 3%Cu, 96%Ag
7) 100%C

Mechanical Testing of Brazed/Soldered Joints

Tube Tensile Test



Butt Strap Tensile Test



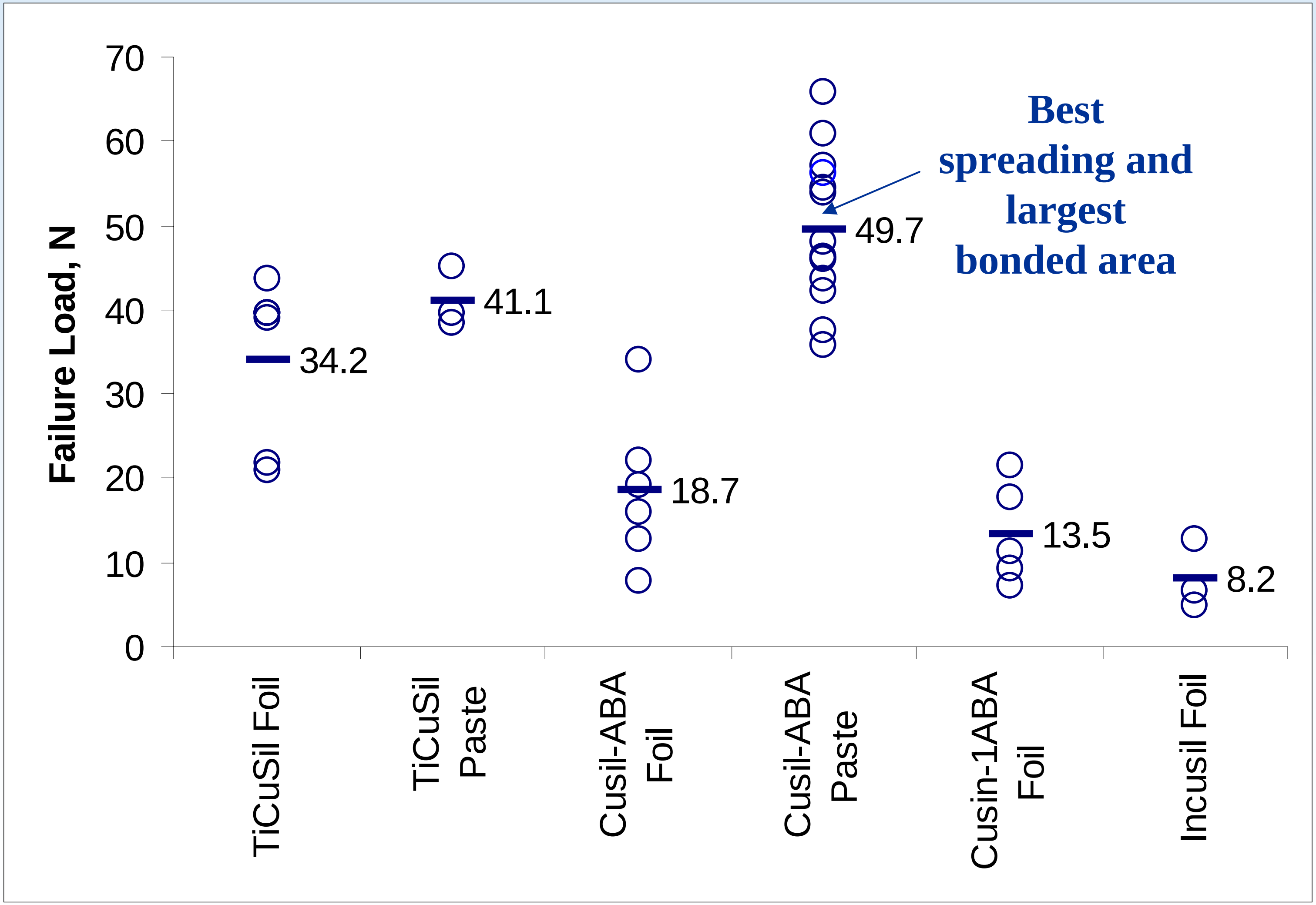
Factors to consider:

-Braze composition, Processing variables

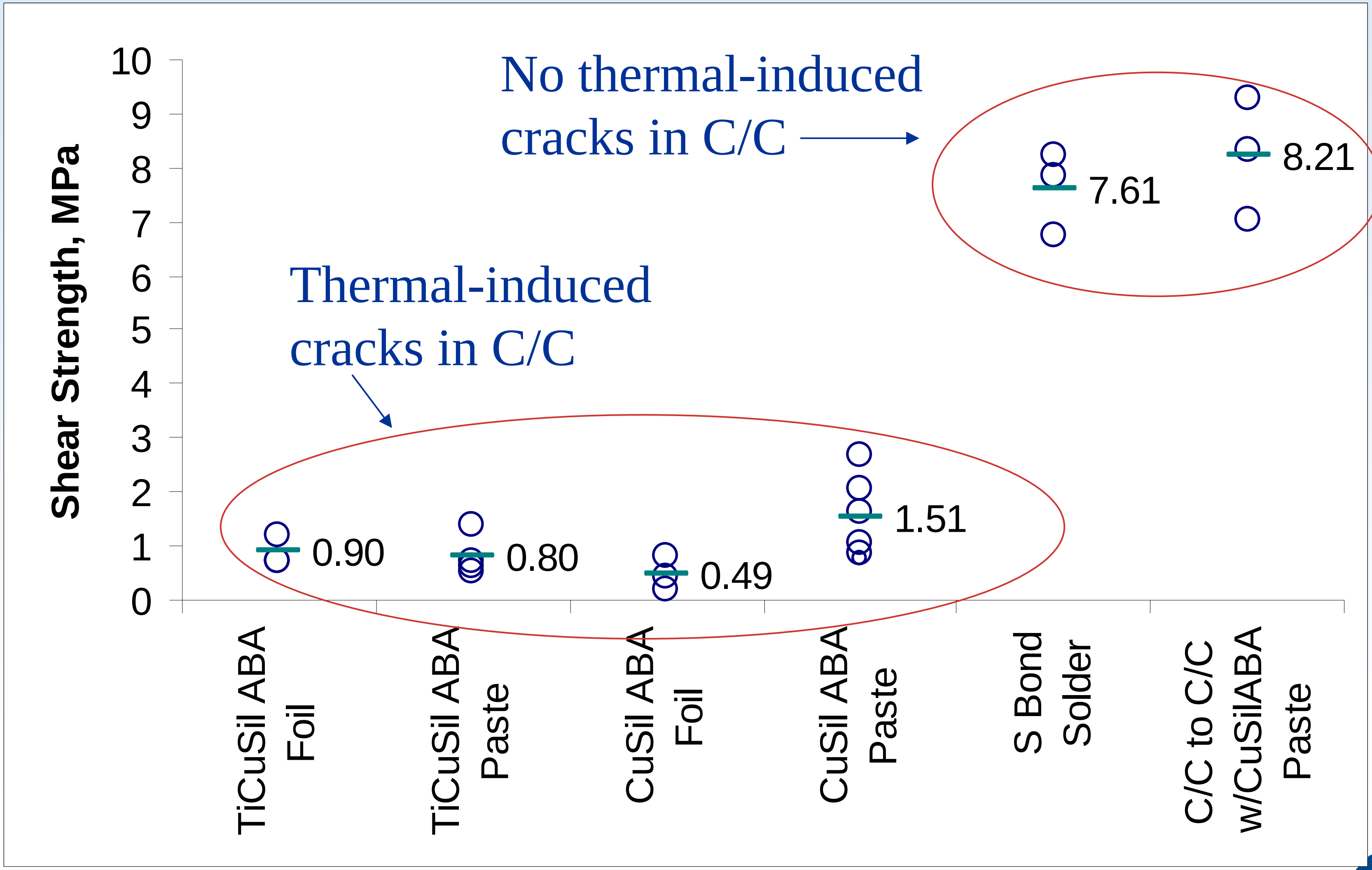
-Bonded area, Location of failure

-Architecture effects

Tube Tensile Test Data for Brazed Joints

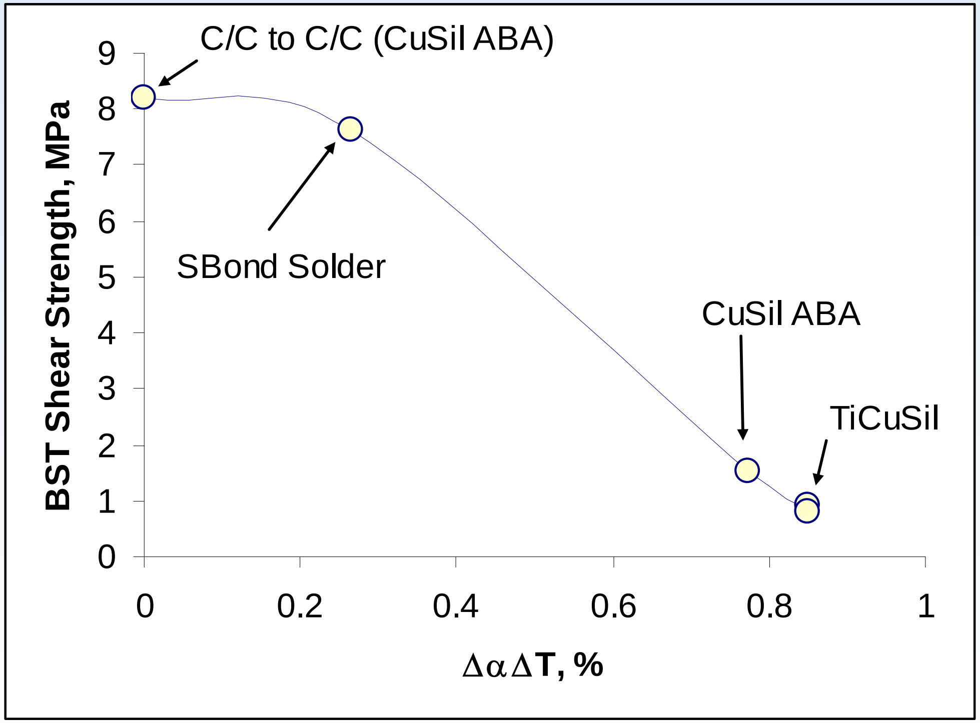


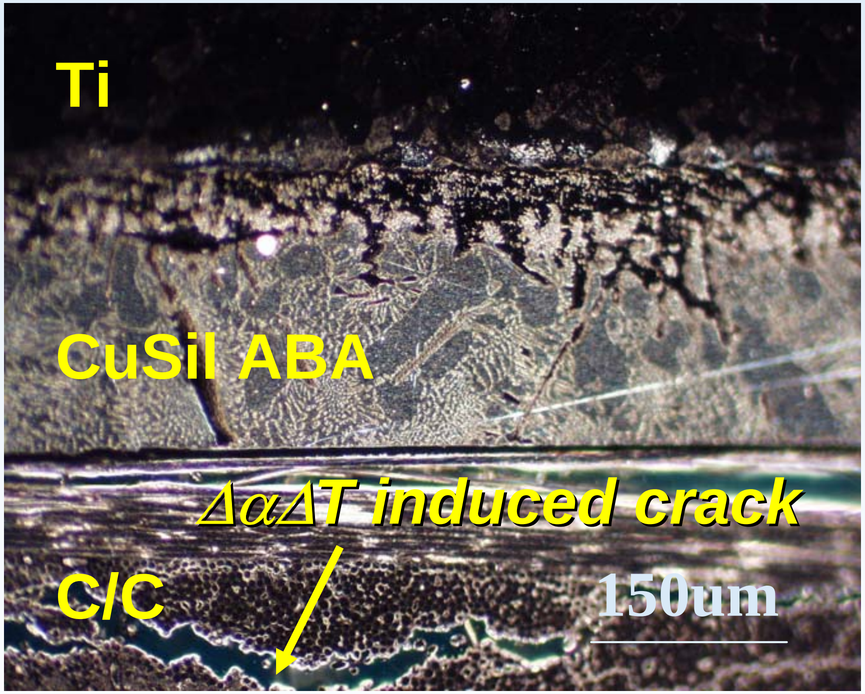
Butt Strap Tensile (BST) Test Data



Thermally-Induced Cracking in C/C Controls Shear Strength of Brazed Joints

For braze materials where there was strong bonding between the braze and the C/C and failure occurred in the outer-ply of the C/C





$\Delta\alpha = \alpha$ **(Ti) – α (C/C)**

ΔT = T (liquidus ~ processing) – 25^{o}C

Joint Material	Proc. Temp., C
S-Bond	~ 300
CuSil ABA	830
TiCuSil	910

Adhesive Bonding of Titanium to C/C Composites

Typical Properties of Commercial Adhesives

Adhesive	Company	Base	Filler	Thermal conductivity W/m-°K	Maximum Rated Temperature (°F) ---------> (K)	
Ceramabond 865	Aremco	ceramic	Aluminum Nitride	170 **	3000	1922
Pyro-duct 597	Aremco	inorganic system	silver	9.1	1200	922
Aremco-Bond 805	Aremco	epoxy	aluminum	1.8	572	573
Staystik 501/ 101	Cookson	thermoplastic	silver	3-3.5	575 *	575
Resbond 931	Cotronics	99% pure graphite	graphite	8.65	5400	3255
Resbond 931C	Cotronics	ceramic bonded graphite	graphite	5.78	2500	1644
Resbond 950	Cotronics	metallic/ceramic composite	Aluminum	6.35	1200	922
Resbond 903HP	Cotronics	ceramic	alumina	5.78	3250	2061
Resbond 906	Cotronics	ceramic	magnesia	5.78	3000	1922
Duralco 124	Cotronics	epoxy	silver	7.2	650	616
Duralco 133	Cotronics	epoxy	aluminum	5.78	600	589
122-39	Creative Materials	epoxy	Aluminum Nitride	108 **	450 ****	505
102-32	Creative Materials	silicone	Silver	12.1	500 ****	533
GC	Dylon	100% carbonaceous	graphite	unknown	5000	3033
EP45-HTAN	Masterbond	epoxy	Aluminum Nitride	3.6	500 ****	533
SS-26	Silicone Solutions	silicone	Silver	unknown (high)	500 **	533
SS-35	Silicone Solutions	silicone	alumina	0.63	500 ***	533
Tra-Bond 813J01	Tra-Con	silicone	Undisclosed	1.1	500 *	533
FM 680	CTYEK	polyimide	Undisclosed	unknown (low)	700	644

*Listed as 575 to 700F (575 to 644 K)

**Theoretical, based on the thermal conductivity and % of filler.

***Maybe capable of higher temp, only tested to 500. Silicone stiffens but keeps adhesion above 500.

****Rated by manufacturer to this temperature and "above". Actual high temperature capability limit is untested.

Adhesive Testing and Evaluation (Schematic)

Screen and order top (20) adhesives based on literature review

Substrates: P120 (pitch based + CVI carbon) C/C from BFG and CP grade 2 Ti plates, as received without and surface treatment.

Make three ½" x ½" samples of each adhesive for microscopy: as cured, heat treated @ 325C (600K) for 24 hours, and liquid nitrogen (-196C/77K) for 15 minutes.

Poor performance considerations:
These are extreme thermal conditions, if results are poor, can back down high temp to 530K and quench slowly to low temp.

Evaluate microstructure for bond quality, voids, etc.

Poor performance considerations:
Poor Ti bond may be amended by etching/abrading Ti surface. Primers can be used on C/C surface. Vacuum may be needed to remove air incorporated by mechanical mixing.

Microstructure
Poor Results:

Re-evaluate adhesive selection and parameters, make new samples to reflect adjustments

Microstructure
Good Results:

Down-select to top adhesives

Make samples for testing using sample mount for uniformity:

1" circle sandwiches: (1) for thermal conductivity, (5) for tensile test

Butt Strap shear test – (5) each for RT and HT testing: (1) ½ x 1" BFG C/C bonded to (2) ½ x 3" Ti plates, ¼" overlap

Testing:

Thermal Conductivity

Mechanical - tensile and shear using ASTM C297 sandwich tensile and butt strap shear at first RT then HT

Down-select to top (3) adhesives

Additional testing and evaluation:

Life cycle/aging with thermal cycling

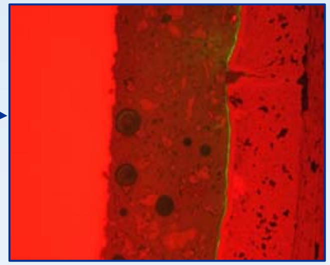
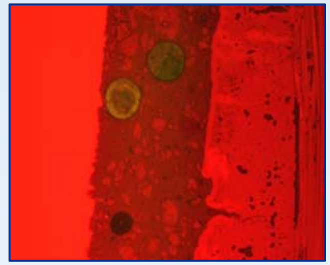
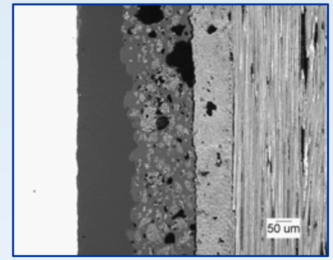
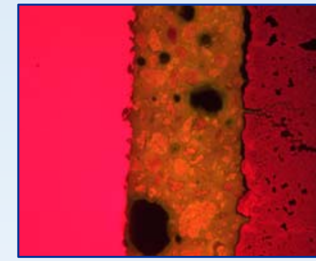
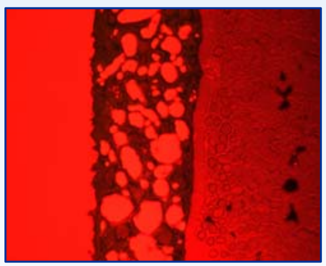
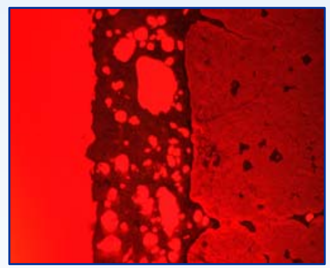
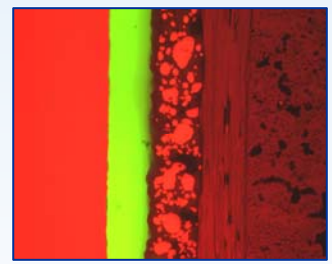
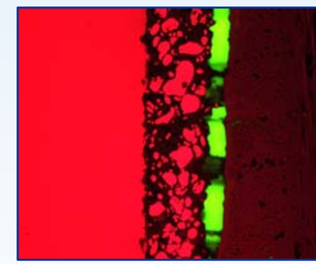
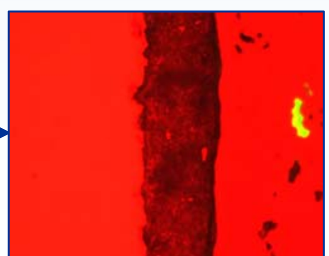
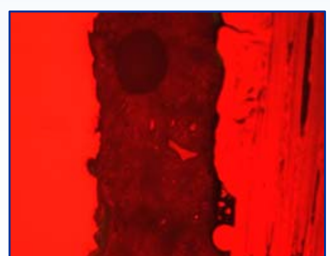
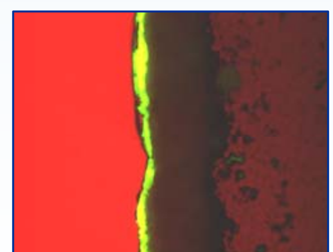
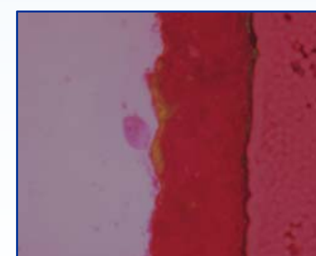
Radiation

Microscopy

Currently working on

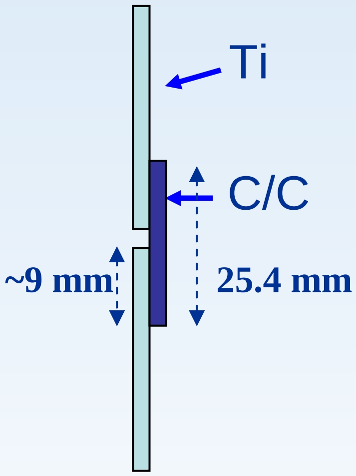
Completed

Microstructure of Adhesive Bonded Ti-C/C Composite Specimens

	As Cured	Liquid Nitrogen, 15 minutes	Heat Treated 600K with untreated titanium	Heat Treated 530K with roughened titanium
Master Bond EP45HTAN, aluminum nitride filled epoxy rated to 533K. 100x	 ok	 ok	 Failure at Ti	 ok
Aremco Resbond 805, aluminum filled epoxy rated to 573K. 100x	 ok	 ok	 Failure at Ti	 Failure at c/c
Tra-Con Tra-Bond 813J01, fibrous alumina and silicon filled silicone rated to 500F. 200x	 ok	 ok	 Failure at Ti	 Failure at Ti

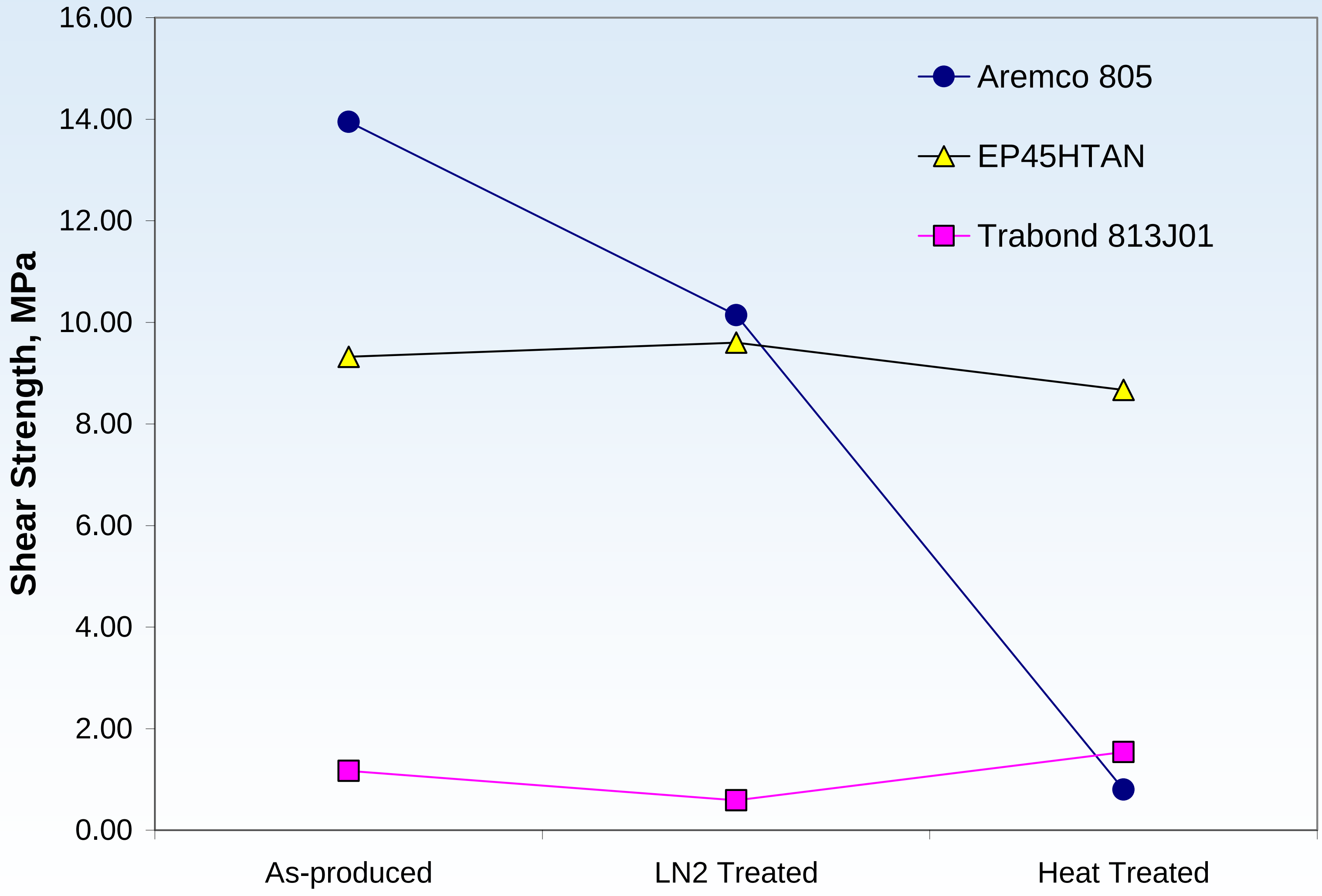
Mechanical Testing of Adhesive Joints

- **Butt-Strap Tensile Test**
  - 12.7 mm wide by 25.4 mm long C/C composite bonded to two 12.7 mm wide Ti pieces
  - Tested at RT:
    - as-produced
    - after a liquid nitrogen (15 min) treatment
    - after 530 K (24 hr) heat treatment
- **Ti bonded to P120 CVI C/C (Goodrich)**
- **Three Adhesives Tested:**
  - Aremco-Resbond 805
  - Tra-Con- Tra-Bond 813J01
  - Masterbond- EP45HTAN
- ***Future tests will include additional adhesives and testing at elevated temperatures***



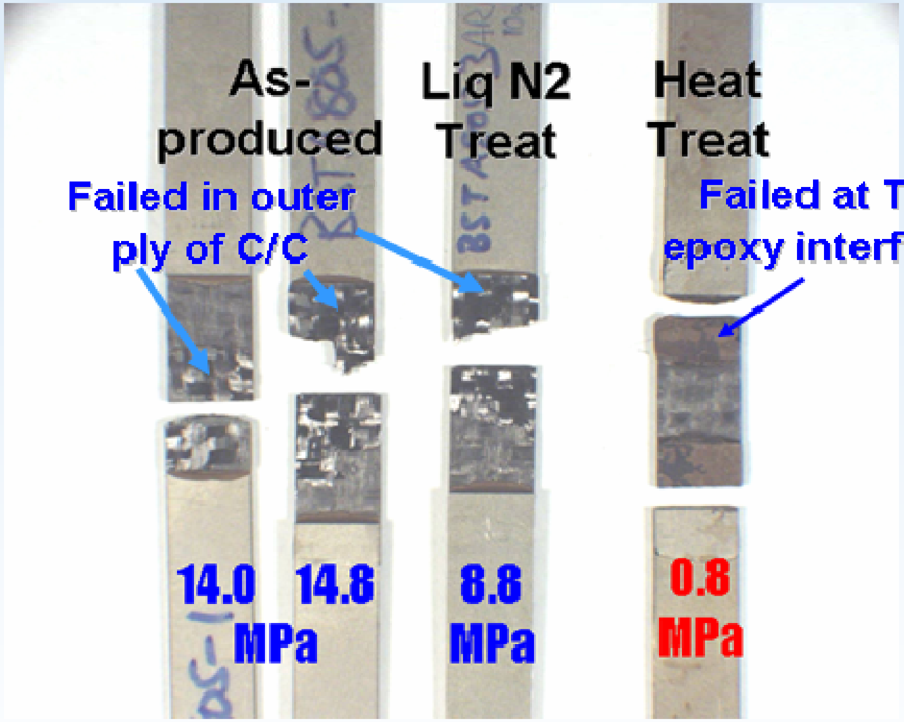
Butt Strap Tension

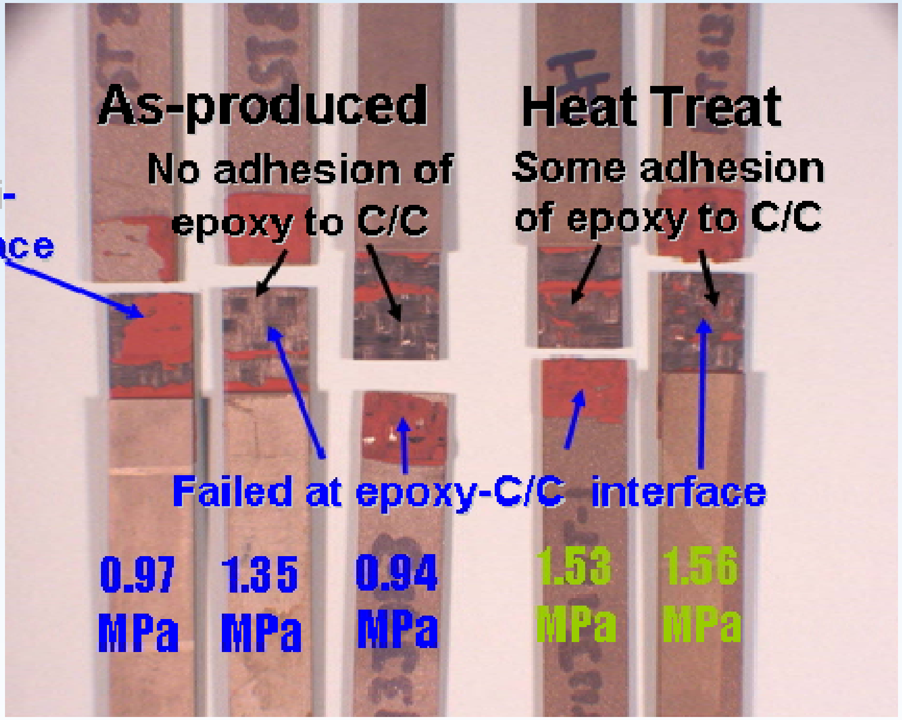
Shear Strength of Adhesive Joints



Fracture Surfaces of BST Shear Specimens

- Aremco-Bond 805 and Tra-bond 813J01 adhesives
- <u>RT tested</u> as-produced, Liq N2 treated and heat-treated (24 hr @ 530 K)





Aremco-Bond 805

-Very strong (failed in C/C) for as-processed and LN2 treated
-Weak after heat treatment (change in fracture surface)

Tra-Bond 813J01

-Moderate strength as-produced (no C/C failure)
-Slight increase in strength with heat-treatment (better adhesion?)

Summary and Conclusions

- **Brazing and adhesive bonding technologies are critically needed for the fabrication of heat rejection system components.**
- **Braze/Solder effectiveness is dictated by several issues: wetting, spreading, bonding, and thermal mismatch**
- **Thermal expansion mismatch between C-C/Braze/Titanium and interlaminar properties of C/C composites play a key role in mechanical behavior of joint.**
  - ***CuSil ABA paste was most successful even though not the lowest temperature braze***
  - ***S-Bond Solder had best shear strengths due to low processing temperature***
- **EP45HTAN epoxy has retained highest shear strengths through thermal cycling**
- **A combination of tensile, shear, and subcomponent testing of joints coupled with fracture mechanics based design and analysis is needed to generate useful engineering design data.**